Monitoring the last two (AR) layers in narrow bandpass filters.

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ABSTRACT

The final corrections which might be made in the last two antireflection (AR) layers in the deposition of narrow bandpass filter designs such as might be used for Dense Wavelength Division Multiplexing (DWDM) in the fiber optics communications field were discussed in a previous report. A broader range of techniques and simulations of those final layer adjustments are described here, how they can be done, and the benefits which might be obtained. A surprisingly simple new technique is given which should yield improved results.

Keywords: narrow band filter coatings, monitoring, error correction, film thickness monitors

1. INTRODUCTION

We have previously reported[1-5] on the simulation of errors in the termination of layers by optical monitoring at their design thicknesses and the effects on filter performance of noise/errors in the monitoring signal. These studies have been for narrow bandpass (NBP) filters such as might be used in telecommunications. The same example filter design for DWDM is used here as was used before, namely: (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)8 1L .52072H .86628L. The indices are 2.05 for H and 1.45 for L.

The effects of random errors in layer termination are simulated, with the natural error compensation properties of the commonly used "turning point" (TP) optical monitoring technique. The three cavity filter design as given above has 114 layers. The common monitoring technique is to terminate each new layer at the TP where the transmittance of the part being monitored passes through a point of inflection and changes direction. This is normally at a point of integral quarter wave optical thickness (QWOT). If a previous layer termination was in error before or after the TP, the current layer would be correspondingly thicker or thinner than a QWOT when the current layer is terminated at the next TP. When this technique is used, errors from previous layer terminations are largely compensated, and we have discussed[1-6] the necessary conditions to take advantage of this effect.

The errors have been simulated as having a random distribution in percentage of transmittance imposed on the sensing of each TP termination in sequence, and then the next TP was found. Three types of cases were previously simulated[1]: 1) where the errors are entirely on the short side of the TP (before), 2) where the errors were symmetrically distributed (centered) about the ideal TP, and 3) where the errors extend from the TP to greater thickness (after), as might be more typical of an actual case. The results show general symmetry about the centered case and similar effects of errors for all three types. The cases presented here, therefore, are with all of the errors after the TP, which is the most likely in practice.

2. TYPES OF FINAL LAYER MONITORING TECHNIQUES

There are a variety of ways in which the final two AR layers can be monitored and terminated as the required thickness has been deposited. Each has its merits and shortcomings. Two "physical" and two optical monitoring techniques will be considered here. The physical thickness techniques considered are: 1) the use of a crystal thickness monitor which responds to the mass of material deposited and 2) the "time at rate" technique. The former can be calibrated to correlate with the optical thicknesses deposited. The latter is commonly used in sputtering processes where the rates are sufficiently constant and stable that the resulting layer thicknesses can be controlled by the length of time of the deposition at a given rate. The two optical monitoring techniques considered are single wavelength optical monitoring (SWOM) as is commonly used in DWDM processes, and broad-band optical monitoring (BBOM). In this latter case, the broad band is only the width of the passband of the filter (~0.3 nm). We are not aware of this being used at this time. This BBOM might be implemented by scanning a "single" wavelength over the required band at an adequate speed to serve the process. There might also be ways to implement a source of the width needed with a laser and/or a

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monochromater. For the purposes of the rest of this discussion, the two physical thickness schemes will be considered as a group and referred to as physical thickness monitoring (PTM).

In a recent paper[1], it was shown that satisfactory choices of thickness for the last two layers could be ***predicted*** from a knowledge of the optical monitor reflectance/transmittance of the filter just before the last two layers are deposited. More details of this prediction technique will be given below. That work was based on SWOM and is extended in this paper to predictions based on using BBOM. These thicknesses will be referred to a ***S-predicted*** (SP) and ***B-predicted*** (BP). The design or ideal thicknesses for the last two layers in the absence of any errors will be referred to as ID. Turning point monitoring can be used with both SWOM and BBOM, where the latter is based on the overall broadband response as compared with its target or goal. TP monitoring by SWOM will be referred to as STP and with BBOM as BTP.

The variables available then are: two layers (113 and 114), three types of layer thickness goals (ID, SP, and BP), and three choices of monitoring techniques (PTM, STP, and BTP). This would allow a myriad of permutations and combinations. When the less logical combinations are eliminated, there are seven cases of interest which will be examined here. These are:

Case 11, where both layers are terminated at ID by PTM;
Case 14, where the next-to-last (NTL) layer (number 113) is terminated at ID by PTM and the last layer by STP;
Case 15, where the NTL layer is terminated at ID by PTM and the last by BTP;
Case 22, where both layers are terminated at SP by PTM;
Case 24, where the NTL layer is terminated at SP by PTM and the last by STP;
Case 33, where both layers are terminated at BP by PTM;
Case 35, where the NTL layer is terminated at BP by PTM and the last by BTP.

As illustrated in Fig. 1, the NTL layer is not a QWOT and does not pass a TP when monitored at the design wavelength. Therefore, something other than the TP monitoring technique must be used, such as PTM. It would also be possible to terminate the NTL layer after a certain photometric change in the optical monitoring signal. However, that will be considered equivalent in this study to the PTM technique for the NTL layer. The last layer, is also not a QWOT, but in combination with the NTL layer it reaches a TP where it can be terminated by an optical monitor to give a maximum of transmittance for the filter at the design/monitoring wavelength.

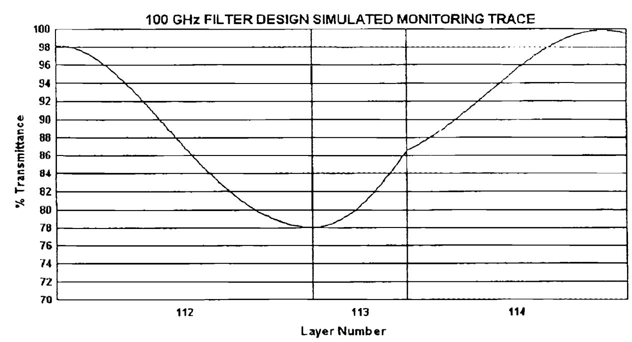

Figure 1. Ideal optical monitor trace at the design wavelength for the last three layers of the design.

Cases 11, 22, and 33 are all done by simple PTM and differ from each other only by the target thicknesses. These thicknesses for the design Case 11 are 98.4H and 231.5L (nm), and for Cases 22 and 33 are predicted from %R. Cases 14 and 24 use a single wavelength optical monitor to terminate the last layer at its TP. This should produce maximum transmittance at the monitoring wavelength, and these are probably most like the techniques used in the industry at this time. Cases 15 and 35 require a BBOM of the special type mentioned above to terminate the last layer at the TP of the BBOM. This should produce maximum transmittance over the passband wavelengths. These BBOM techniques are probably ***not*** used in the industry for this application at this time.

3. BASIS OF PREDICTED THICKNESSES

The most readily available information from which to predict the best thicknesses of the NTL and last layer for SP and BP is the monitor signal transmittance (T) of the filter just before the NTL layer is to be deposited. This T signal has been the basis of all of the layer termination decisions up to that point in the filter deposition, therefore it is readily available. For purposes of discussion, we will also use the reflected intensity (R) which is equal to 1-T (because there is no significant absorption involved). The use of R instead of T is partially because it is convenient to illustrate some aspects of the process on a Reflectance Amplitude Diagram (RAD). Figure 2 is a section of such a RAD, the properties of which are described in detail elsewhere[6]. These RAD's are actually the reflectance amplitude (r) whose magnitude is the square root of R, or R = rr*, where r* is the complex conjugate of r. This r and an associated phase angle define a point within the limiting circle of r = 1 on the RAD. On such a diagram, the filter deposition starts on the uncoated substrate with R of about 4% or 0.04. When the Fresnel reflection coefficient is calculated for a substrate of index 1.5 in air, r is equal to -0.2 or a magnitude of 0.2 and phase angle of 180°. This is 1/5th of the way from the origin of coordinates to the bounding circle (r = 1.0) to the left of the center on negative the real axis.

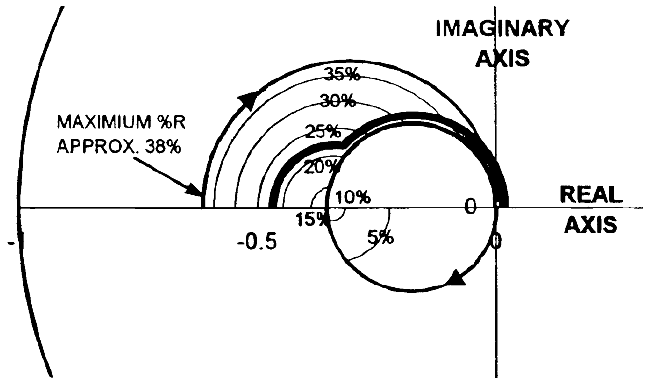

Figure 2. Reflectance amplitude diagram of the range of loci for the last two layers which will provide zero reflectance (100%T) at the design wavelength. Curves are labeled with the %R at the end of the 112th layer and the starting point for the 113th (NTL) layer.

As the first 112 layers of this design are deposited, the r point moves clockwise on semicircles which would each ideally end on the horizontal real axis of the RAD. At the end of the 112th layer, the r point, in most cases, would be in the vicinity of r equal to –0.4 to –0.5 or with %R between 16 and 25%. In Fig. 2, the ID starting point would be at the left end of the bold set of partial circles. There is a much greater range of "correctable" r points for the end of layer 112 which are encompassed by the largest partial circle in Fig. 2. This circle is labeled "Maximum %R Approx. 38%" and the minimum %R would be 0%. However, the examples shown in this paper have almost all been in the range of about 19-25%R. Because the goal is to have terminated layer 112 right at the TP, the r of its end point should be on the real axis except for the influence of the small phase angle errors which would cause it to fall a small distance before (below) the negative real axis or above (after) it. Therefore, the salient feature to use in our calculation/prediction is the magnitude of r which we can measured by R (or 1-T). The small phase errors from the nominal 180° can be ignored.

In examining Fig. 2, we see that the locus of a typical last two layer pair moves on the locus of the high index material (of the NTL layer) clockwise from the starting point near the negative real axis until it intersects and transfers to the low index material locus circle which then passes through the origin where r and %R equal zero. In the unlikely case where the starting R is less than 12.6%, the locus of the high index layer starts by moving downward until it intersects the low index path to the origin. For the special case of R equal to 12.6%, no high index layer is required. Any thickness of H could be used because the high index locus would only stay at that same spot, since it is the center of the H circles.

The thicknesses (**t** in nanometers) of high and low index layers required in the SP cases to move from a given %R to zero reflectance at the origin are plotted in Figs. 3 and 4. It can be seen that over a region broader than might be of practical interest (15-30%), both of these are well approximated by a linear function of %R at the end of layer 112 (illustrated by the thin straight lines). Therefore, we can use the linear equations Eqn. 1 and 2 which are shown and plotted on each figure to predict the high and low index layer thicknesses needed to bring the reflectance to zero at the design wavelength. Even in the region around 12.6%R, the linearly predicted high index thickness can be shown to work well because of the insensitivity to thickness in the range mentioned above.

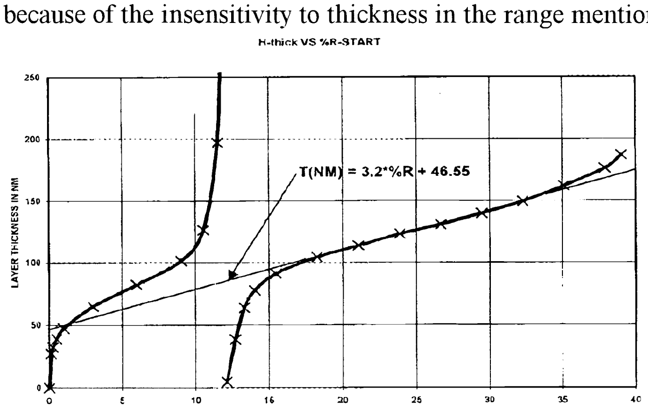

Fig. 3. Ideal thickness for the high index NTL layer versus %R at the start of the layer to produce (with the last layer) loss at the design/monitoring wavelength.

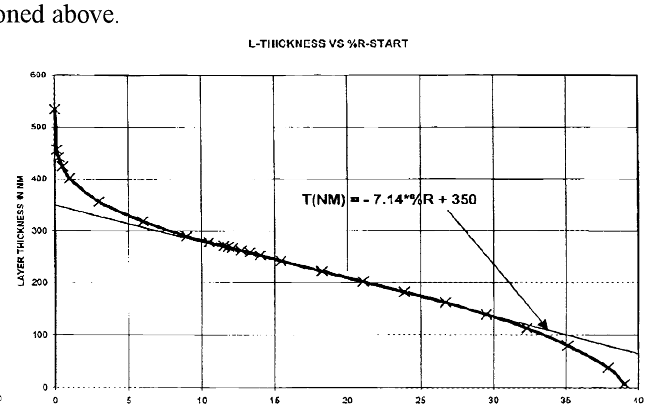

Fig. 4. Ideal thickness for the last low index layer versus %R at the start of the layer to produce(with the NTL layer) no reflection loss at the design wavelength.

$$t_{113}(nm) = 3.20\ R + 45.6. \quad (1)$$

$$t_{114}(nm) = -7.14\ R + 350. \quad (2)$$

Equations 3 and 4 have been similarly derived for the BP (broad band optical monitor TP) cases.

$$t_{113}(nm) = 3.58\ R + 23.9. \quad (3)$$

$$t_{114}(nm) = -3.08\ R + 294. \quad (4)$$

4. EFFECTS OF FINAL LAYER MONITORING TECHNIQUES

We will now compare in Figs. 5 through 11 the spectral results of using these seven different approaches. In all of these figures, there are ten spectra simulated with random errors of 0.20%T that are all after the TP. The ideal design spectra is also plotted in the background of each figure. The last two layers are simulated with no random errors, since that would not be expected to significantly influence the results. Whether a crystal monitor or time and rate were used, we would calibrate those thicknesses based on the crystal readings or time and rates from the previous few layers of the same materials which preceded the 113th layer. Each case is ranked below from 7th to 1st (also including results not shown from centered as well as "all after" errors) with respect to its probable merit in satisfying a "minimum transmittance in the passband" requirement.

Figure 5 shows Case 24 with a SP NLT layer and STP termination of the last layer. This performs well at the monitoring wavelength (1550 nm), but is one of the least satisfactory over the passband. It appears to be generally true that optimizing for the single monitoring wavelength is not optimal for the broad band that is of interest. Figure 6 shows Case 22 where both layers are terminated by PTM at the best SP thicknesses, and this is also good at the monitoring/design wavelength, but not over the passband. Case 14 seen in Fig. 7 is slightly better using the ID for the NTL layer and STP for the last.

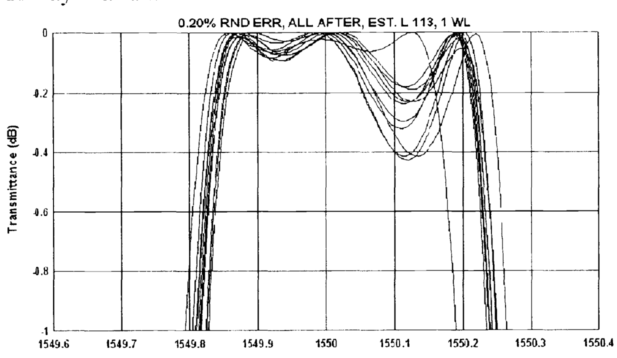

Fig. 5. 7th ranked, Case 24 where the single wavelength *predicted* thickness for the high index NTL is terminated physically, but the last layer is terminated *optically* at the TP using single wavelength monitoring.

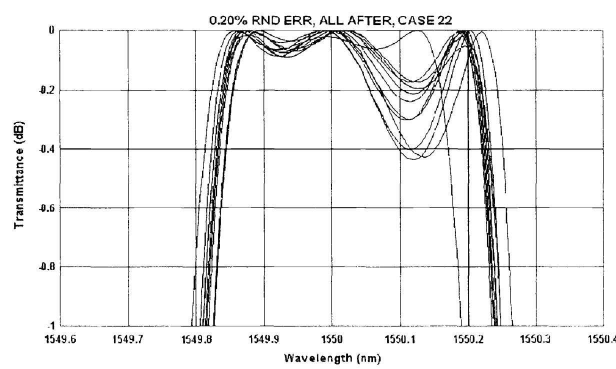

Fig. 6. 6th ranked, Case 22 where *both* of the last two layers are terminated at the single wavelength *predicted* thicknesses by physical rather than optical monitoring.

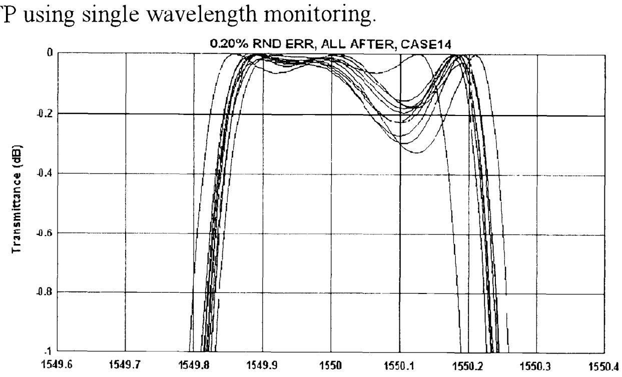

Fig. 7. 5th ranked, Case 14 where the *design* thickness for the high index NTL is terminated physically, but the last layer is terminated *optically* at the TP using single wavelength monitoring.

Case 11 seen in Fig. 8 where both layers are terminated by PTM at the ID thicknesses show good performance over the passband. However, this case does not reach the high transmittance of the cases above at the design/monitoring wavelength. Figure 9 shows Case 15 where the NTL layer is terminated by PTN at the ID thickness and the last layer by BTP. This gives a somewhat better result than Case 11

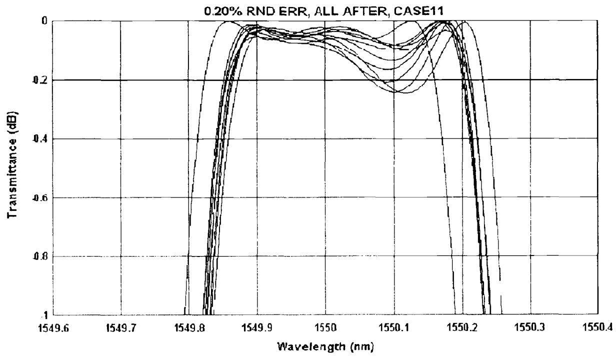

Fig. 8. 4th ranked, Case 11 where *both* of the last two layers are terminated at the ideal *design* thicknesses by physical rather than optical monitoring.

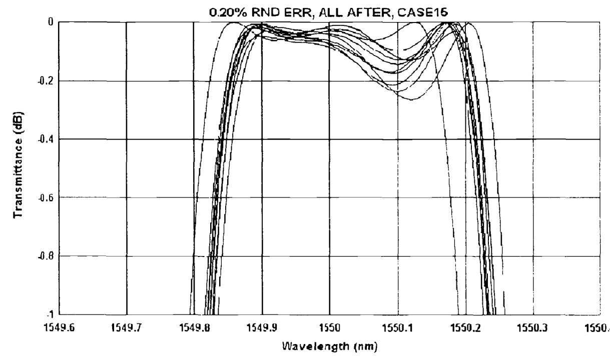

Fig. 9. 3rd ranked, Case 15 where the *design* thickness for the high index NTL is terminated physically, but the last layer is terminated *optically* at the TP using BBOM.

(when the centered case results are considered), but at the expense of a more complex hardware system using BBOM. Case 33 shown in Fig. 10 is particularly interesting in that it gives nearly the best results with simple PTM at BP thicknesses for both layers. Figure 11 shows Case 35 which achieves the best performance with PTM at the BP thickness for the NTL layer and BTP for the last layer. However, this case again requires the more complex system using BBOM.

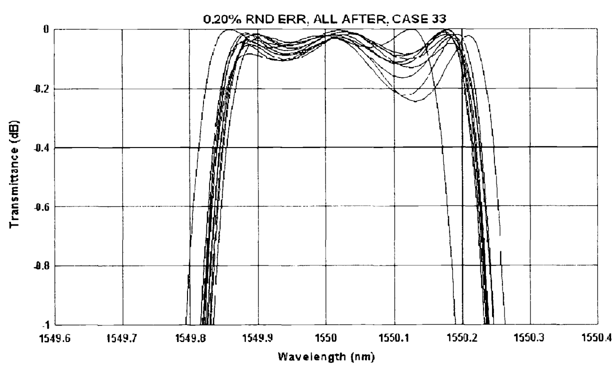

Fig. 10. 2nd ranked, Case 33 where *both* of the last two layers are terminated at the broad band *predicted* thicknesses by physical rather than optical monitoring.

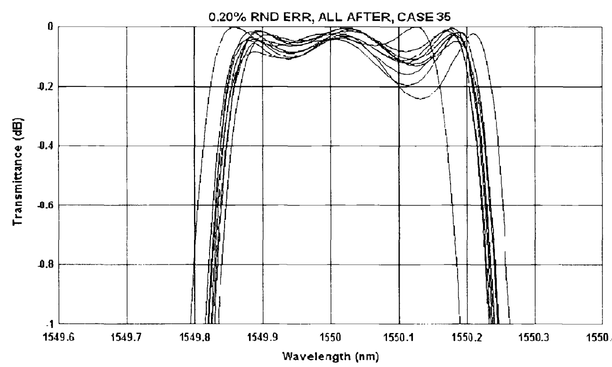

Fig. 11. 1st ranked, Case 35 where the broad band *predicted* thickness for the high index NTL is terminated physically, but the last layer is terminated *optically* at the TP using broad band optical monitoring.

5. CONCLUSIONS

Seven practical approaches to the monitoring of the final two layers of a narrow bandpass filter design have been simulated and compared. It has been found that optimizing the performance at the monitoring wavelength may be somewhat detrimental to desired performance in the passband. It has however been found that almost optimal performance can be achieved in the presence of monitoring errors by the relatively simple approach of terminating the last two layers by physical thickness monitoring at thicknesses which have been predicted for the best performance over the passband. The technique uses the information from the level of the optical monitoring signal at the end of the filter deposition just before the last to layers. The best thicknesses for the last two layers is then predicted from predetermined equations. In general, such equations can be derived for any particular narrow bandpass filter design, but are expected to be different from the ones given for this particular example design. We conclude, as an ancillary benefit of examining these results, that the random errors in %T at the turning points can be on the order of 0.20% or possibly greater, depending on the monitoring approach used for the last two layers of the design. This should allow one to obtain a reasonable yield for such a 100 GHz DWDM filter with a 0.3 dB specification on losses in the passband.

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